CORRELATING METEOROLGICAL, SATELLITE, AND GROUND SAMPLING DATA TO DETERMINE SOURCE OF $PM_{2.5}$ AT BAGRAM AIRFIELD, AFGHANISTAN

by

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## COPYRIGHT STATEMENT

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# ABSTRACT

CORRELATING METEOROLGICAL, SATELLITE, AND GROUND SAMPLING DATA TO DETERMINE SOURCE OF $PM_{2.5}$ AT BAGRAM AIRFIELD, AFGHANISTAN

John Kendzie, Masters of Science in Public Health, 2015

Thesis directed by: LTC Christopher Gellasch, Assistant Professor, Department of Preventive Medicine and Biostatistics

Particulate matter (PM) is a mixture of airborne liquid droplets and solid particles. The health concerns associated with PM less than 2.5 micrometers in diameter ($PM_{2.5}$), include both short and long-term health effects such as asthma, bronchitis, cardiopulmonary disease, cancer, and premature death. One source of $PM_{2.5}$ is open burning (i.e. burn pits), which is often the primary means of disposing of solid waste during military operations in combat zones to include Iraq and Afghanistan. Another source of $PM_{2.5}$ is geological material (natural windblown dust), which is common in arid environments. Past research has shown a relationship between $PM_{2.5}$ and, meteorological data, geographic location, and aerosol optical depth (AOD): a measure of how much sunlight is absorbed or scattered by aerosols in a vertical column of air.

This study looked at the association between $PM_{2.5}$ and meteorological conditions and AOD at Bagram Airfield (BAF), Afghanistan using data obtained from the U.S. Army, U.S. Air Force, and the National Aeronautics and Space Administration (NASA). Logistic regression models and geographic information system (GIS) images were used to examine the association between $PM_{2.5}$ data collected at BAF with AOD and meteorological data, and then plot locations of $PM_{2.5}$ sampling sites, possible sources of $PM_{2.5}$ and AOD collection points. Additionally, wind rose diagrams were used to illustrate directional air movement, by season, from burn pit to $PM_{2.5}$ sampling sites in each zone. The results indicate that $PM_{2.5}$ concentrations were lower when wind speed and relative humidity increased. Concluding that increased wind speed may change air patterns and elevated smaller particles ($PM_{2.5}$) higher in the atmosphere, thus reducing the amount collected in the samplers. Additionally, it is possible for larger PM particles to be formed through hygroscopic growth as relative humidity increases; reducing the amount of $PM_{2.5}$ collected during sampling periods. Wind direction was not indicative of higher $PM_{2.5}$ concentrations within zones, indicating that sources other than the burn pit may be the source of the majority of $PM_{2.5}$ at BAF. Identifying the composition of the $PM_{2.5}$ collected on the sampling media may aid in identify the source. Additionally, AOD values were lower as distance increased from the burn pit.

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# ABBREVIATIONS

| | |
|---|---|
| AERONET | Aerosol Robotic Network |
| AFHSC | Armed Forces Health Surveillance Center |
| AFMIC | Armed Forces Medical Intelligence Center |
| AQI | Air Quality Index |
| ANOVA | Analysis of Variance |
| AOD | Aerosol Optical Depth |
| BAF | Bagram Airfield |
| CMI | Chronic Multi-Symptom Illness |
| DESP | Deployment Environmental Surveillance Program |
| DOD | Department of Defense |
| DOEHRS | Defense Occupational Environmental and Health Readiness System |
| DPS | Deployable Particulate Sampler |
| MEGs | Military Exposure Guidelines |
| µg/m3 | Micrograms per cubic meter |
| MODIS | Moderate Resolution Imaging Spectroradiometer |
| NAAQS | National Ambient Air Quality Standards |
| NASA | National Aeronautics and Space Administration |
| OEHS | Occupational and Environmental Health Surveillance |
| PM | Particulate Matter |

| | |
|---|---|
| $PM_{2.5}$ | Particulate Matter 2.5 micrometers in diameter or less |
| $PM_{10}$ | Particulate Matter 10 micrometers in diameter or less |
| PPE | Personal Protective Equipment |
| RMS | Root Mean Square |
| USACHPPM | United States Army Center for Health Promotion and Preventive Medicine |
| USAF | United States Air Force |
| USAPHC | United States Army Public Health Command |
| USEPA | United States Environmental Protection Agency |

# CHAPTER 1: INTRODUCTION

## BACKGROUND AND SIGNIFICANCE

Personnel deployed to combat zones encounter many different types of environmental hazards that are associated with adverse health outcomes (e.g. cancer and respiratory disease) [1]. Many of the environmental exposures are naturally occurring, such as exposure to extreme temperatures, wet or dry conditions, and disease transmitting insects to name a few, while other environmental hazards are created or compounded by the deployed personnel themselves. It is estimated that each deployed individual generates an average of 8-10 pounds of waste per day, creating as much as 42 tons per day at large base camps that must be disposed of. Initially, there are no logistical provisions to rid the base camps of the waste generated. Therefore, open-air waste burning, a practice long used by the military, is often the primary method of disposal in Afghanistan. In fact, 197 burn pits were documented as still in use in Afghanistan as of January 2011 [1]. Waste generated including trash, garbage, dunnage, kitchen waste, medical waste, hazardous waste, human waste, electronic waste etc. may potentially all be disposed of in open air burn pits without any segregation or documentation of what was burned or how often. Burn pits utilized in this manner eliminate waste and reduce the risk of unsanitary conditions and diseases attributed to those conditions. However they also generate potentially hazardous environmental conditions as a result of the combustion emissions.

Potential sources of airborne particulate matter include geological material (soil), aviation operations, vehicle emissions, generator emissions, industrial operations, and various other natural and anthropogenic sources including burn pit emissions. The emissions generated by the combustion of the burned waste is comprised of many chemical byproducts and are commonly referred to as "smoke". The emissions typically contain carbon monoxide (CO), polycyclic aromatic hydrocarbons (PAHs), methane ($CH_4$), volatile organic compounds (VOCs), semi- volatile organic compounds (SVOCs), metals (e.g. lead, cadmium), dioxins (PCDDs), furans (PCDFs) and particulate matter (PM) [2]. The PM varies in size and the mixture of liquid droplets and solid particles found in the air is often referred to as aerosols [3]. The size and composition of the "smoke" emitted by the burn pit depends on multiple variables such as composition of waste, burning temperature, duration, and weather conditions at the time. Unfortunately, little information is available for some of these variables at military base camps overseas.

Short and long-term health outcomes such as acute respiratory illness, eye, nose and throat irritation, and cancer have been associated with environmental hazards. In fact, many personnel who were deployed to areas that utilized burn pits, such as Iraq and Afghanistan, as the primary method of disposal believe that their health problems are a result of being exposed to the smoke generated from the burn pits [1]. Based on these concerns, the Armed Forces Health Surveillance Center (AFHSC) and the Department of Defense (DoD) Center for Deployment Health Research, conducted epidemiologic studies to determine whether adverse health conditions of US service members assigned to locations with burn pits could be attributed to the burn pit emissions. The study looked

at respiratory symptoms and diseases, chronic multi-symptom illness (CMI), cardiovascular diseases, lupus, sleep apnea, rheumatoid arthritis, and birth outcomes of infants of parents who deployed. The result of the study was that all health outcomes of personnel that deployed to areas with a burn pit were about the same or lower compared to personnel that never deployed [4].

However, multiple other studies have shown an association between PM and hazardous health outcomes, to include respiratory infections, asthma, cardiovascular problems, and mortality [5]. These must be considered when evaluating personnel exposed to environments with high volumes of PM for extended periods of time. Respirable particulate matter (PM) is one of the health concerns that personnel deployed to arid regions face. Particulate matter of various diameters (measured in micrometers) has the capability to travel great distances and contaminate surfaces both outdoors and indoors alike. Health concerns affecting the upper respiratory tract have been associated with particles of ten micrometers or less ($PM_{10}$) in diameter, whereas particles with a diameter of 2.5 micrometers or less ($PM_{2.5}$) are associated with health concerns of the lower respiratory tract [6]. Minimal, if any, personal protective equipment (PPE) is available to prevent the inhalation of PM to personnel deployed to these areas and therefore it is likely that all personnel have been exposed to various amounts of PM.

The three main air pollutants in the U.S. Central Command CENTCOM, including Afghanistan, include geological dust, smoke from burn pits, and heavy metal condensates from industrial activities [7]. Geological dust exists naturally in the

environment and is difficult to control on a large scale in arid conditions such as Afghanistan where dust storms are typical.  However, watering, laying gravel or asphalt, and limiting movement can be used to limit the amount of airborne geological dust that enters the breathing zone.  Burn pits are doctrinally used early in U.S. military deployments when waste management systems including recycling, land-filling, and incinerations are not an option to dispose of the majority of solid waste (mixed waste) [1].  Disposing of mixed waste (metal, plastic, rubber, electronics, batteries, fuel etc.) through the use of burn pits creates a plume of smoke that may include lead, zinc, and cadmium as airborne particulates and cause potential health effects if inhaled [8].  Health conditions related to the inhalation of air with elevated PM have been found to be correlated to events where temperature inversions occurred.

Temperature inversions typically occur when cold air is trapped under a layer of warm air which can occur when the ground cools rapidly on a cold clear night or when cold air from snowcapped mountains rolls down and collects in a valley or "basin" formed by the topography of the area as seen in Salt Lake City, Utah and Bagram Airfield, Afghanistan.  The inversions create a stable air mass that trap smog and air pollutants near ground level and  increase the potential to cause negative health outcomes such as the "London Smog" incident in 1952 [9].  Meteorological conditions in Afghanistan where inversions are most likely occur from fall to spring [8].

**$PM_{2.5}$ and the body**

Due to the small size, $PM_{2.5}$ has the potential to penetrate deep into the lungs and induce respiratory diseases [10]. Studies have linked $PM_{2.5}$ to respiratory conditions such as asthma, bronchitis, acute and chronic shortness of breath, and premature death. Pulmonary and cardiovascular health concerns, ranging from minor to serious, have been associated with the inhalation of PM [11] [12]; however, not all personnel who were exposed will become ill or experience the same level of illness. Morbidity and mortality determinants include the PM composition based on environmental and anthropogenic activities, exposure concentration and duration, and the health status of exposed individuals.

Monitoring of air quality in the United States (U.S.) is the responsibility of the United States Environmental Protection Agency (EPA). The EPA uses 24-hour averages of dry PM to determine air quality using community-oriented (core) sites. The core sites (approximately 1500) are located throughout the US and represent average $PM_{2.5}$ exposure of the communities in which they are located; forming the basis of the $PM_{2.5}$ network. The $PM_{2.5}$ network is maintained by federal, state, and local agencies and provides the capability to compare $PM_{2.5}$ National Ambient Air Quality Standards (NAAQS) (Appendix A), using mass-only sampling to detect ambient concentrations of $PM_{2.5}$ over a 24-hour period. The federal Clean Air Act requires the EPA to set National Ambient Air Quality Standards (NAAQS) for pollutants to protect the health of all persons in the United States, including vulnerable populations. The EPA standards cover

six major air pollutants, also known as “criteria” pollutants: ozone, particulate matter (PM), carbon monoxide, nitrogen oxides ($NO_x$), sulfur dioxide, and lead.

Understanding that air quality is also a concern to personnel and equipment in deployed environments the Department of Defense (DoD), lead by the United States Army Public Health Command (USAPHC), formerly known as the United States Army Center for Health Promotion and Preventive Medicine (USACHPPM), established the Deployment Environmental Surveillance Program (DESP) and developed a specific methodology for PM and established the military exposure guidelines (MEGs). The MEGs were developed using a combination of PM risk assessments in deployed environments, the USEPA's NAAQS and Air Quality Index (AQI) (Appendix B). The MEGs identify three "Hazard Severity" categories and possible health effects associated with short and long-term exposure based on the concentration of PM in the air (Tables 1 and 2) [13].

Table 1: Short-Term (24-hour) Particulate Matter Air-MEGs

| Hazard Severity | $PM_{2.5}$ | $PM_{10}$ | Description of Military Health and Operational Effects |
|---|---|---|---|
| Critical | 500 μg/m$^3$ | 600 μg/m$^3$ | Above these, most if not all personnel will experience very notable eye, nose, and throat irritation and respiratory effects. Visual acuity is impaired, as is overall aerobic capacity. Some personnel will not be able to perform assigned duties. Some lost-duty days are expected. Those with a history of asthma or cardiopulmonary disease will experience more severe symptoms.** Conditions may also result in adverse, non-health related materiel/logistical impacts. |
| Marginal | 250 μg/m$^3$ | 420 μg/m$^3$ | Above these, a majority of personnel will experience notable eye, nose, and throat irritation and some respiratory effects. Some lost-duty days are expected. Significant aerobic activity will increase risk. Those with a history of asthma or cardiopulmonary disease are expected to experience increased symptoms.** |
| Negligible | 65 μg/m$^3$ | 250 μg/m$^3$ | Above these, a few personnel may experience notable mild eye, nose, or throat irritation; most personnel will experience only mild effects. Pre-existing health conditions (e.g., asthma, or cardiopulmonary diseases) may be exacerbated.** |

Notes:
* The MEGs and descriptors are based on professional judgment reflecting a consensus opinion of USAPHC subject matter experts.
** Diagnosis of pulmonary or cardiopulmonary diseases would prevent deployment, though some conditions may go undetected. A small percentage of deployed personnel fall into this sensitive group.

The annual NAAQS for $PM_{10}$ were revoked in 2006 by the USEPA due to lack of evidence that linked health problems to long-term exposure, therefore USAPHC no longer recommends any long-term MEGs for $PM_{10}$ and is listed as "Not defined" (Table 2). The EPA associates any health risks related to long-term exposures to PM are primarily due to $PM_{2.5}$[13].

Table 2: Long-Term (1-year) Particulate Matter Air-MEGs

| Hazard Severity | $PM_{2.5}$ | $PM_{10}$ | Description of Military Health and Operational Effects |
|---|---|---|---|
| Marginal | 65 µg/m$^3$ | Not defined | With repeated exposures above this, it is plausible that development of chronic health conditions such as reduced lung function or exacerbated chronic bronchitis, chronic obstructive pulmonary disease (COPD), asthma, atherosclerosis, or other cardiopulmonary diseases could occur in generally healthy troops. Those with a history of asthma or cardiopulmonary disease are considered to be at particular risk. This guideline is an uncertain screening value—it is not a known health effects concentration. |
| Negligible | 15 µg/m$^3$ | Not defined | With repeated exposures above this, it is considered possible that a small percentage of personnel <u>may</u> have increased risk for developing chronic conditions, such as reduced lung function or exacerbated chronic bronchitis, COPD, asthma, atherosclerosis, or other cardiopulmonary diseases. Personnel with history of asthma or cardiopulmonary disease are considered to be at particular risk. Exposures below this are not expected to result in development of chronic health conditions in generally healthy troops. |

Note:
* The MEGs and descriptors are based on professional judgment reflecting a consensus opinion of USAPHC subject matter experts. USAPHC no longer recommends long-term MEGs for $PM_{10}$. The Negligible MEG is the USEPA NAAQS standard reflecting a threshold level for the general population based on studies evaluating primarily children or individuals with cardiovascular and other diseases. Alternative standards for healthy adults do not yet exist. This MEG is considered a point of departure for further consideration and is not an action level.

The DoD conducts mass-only sampling, achieved by using pre-weighed filters in air sampling devices. The military monitors air quality by drawing in a known volume of air over a specified period of time and then re-weighing the filter to determine how much PM (mass) was collected. The amount of PM can retrospectively be compared to the NAAQS to determine what the AQI was for that period of time. Currently, there is no real-time analysis within the DoD to determine air quality. Results of PM samples may take weeks or months as all samples must be shipped from the collection site to USAPHC-Main in Aberdeen Proving Ground (APG), Maryland for analysis. Additionally, after being weighed, the filters can be dissolved using an established scientific method determine the composition or speciation of the $PM_{2.5}$. Identifying and

understanding the speciation of the $PM_{2.5}$ is important, as it helps to determine the source of the pollution and indentify possible causes of health outcomes of exposed personnel. All data are archived in the Defense Occupational and Environmental Health Readiness System (DOEHRS) and can be used in retrospective studies, policy development, and to identify and treat exposure-related injuries and illnesses [14]. Additionally, the USAPHC collaborates with the Armed Forces Health Surveillance Center (AFHSC) to improve the intelligence preparation of the battlefield using the data obtained from deployed environments.

**Satellite Aerosol Optical Depth**

The National Aeronautics and Space Administration (NASA) estimates air quality around the world using satellite reflectance data to produce several atmospheric products including Aerosol Optical Thickness also known as Aerosol Optical Depth (AOD). NASA defines AOD as "the degree to which aerosols prevent the transmission of light by absorption or scattering of light". One way that AOD is measured is by using Moderate Resolution Imaging Spectroradiometer (MODIS) sensors located on the Terra and Aqua satellites as they orbit the earth [15] aboard NASA's Earth Observing System (EOS).

The Terra and Aqua satellites orbit the Earth in opposite directions (Terra, north to south and Aqua, south to north) allowing MODIS to view the entire Earth's surface every 1 to 2 days, passing the same location approximately three hours apart thus providing two opportunities to collect data from each location every day [16]. MODIS

incorporates three algorithms, Dark Target (DT), Deep Blue (DB) and a combination of DT and DB to create a "merged" algorithm which are used to retrieve AOD [17]. The DT and DB retrieval algorithms differ in that DT is used to capture AOD over bodies of water and vegetated land, whereas DB is used to capture AOD over bright surfaces such as sand. The DT/DB combined products uses quality flags to select the best measurement (DT of DB) for each pixel in the image. AOD measures the change in light throughout the entire atmospheric column which is affected by the aerosol mass concentration, mass extinction efficiency, hygroscopic growth, and effective scale height [10]. The basic idea behind AOD is the amount of light reflected from the surface of the earth is affected by the amount of aerosols in the atmosphere.

Previous studies by Wang [10], Kumar [18] and Kloog [19], respectively, have shown correlation between AOD and $PM_{2.5}$ collected at surface using logistic regression models. In 2002, Wang and Christopher explored the relationship of $PM_{2.5}$ measured at surface levels and AOD derived from MODIS by collecting hourly $PM_{2.5}$ at seven locations in Jefferson County, Alabama using the Tapered-Element Oscillating Microbalance (TEOM) instrument. The TEOM has an accuracy of $\pm$ 5 $ugm^{-3}$ for 10 minute averaged data and $\pm$ 1.5 $ugm^{-3}$ for hourly averages. MODIS AOD values were within uncertainty levels of $\pm$ 0.05 $\pm$ 0.20 AOD over land at 10 x 10 $km^2$ when compared against ground based measurements by AERONET [10, 20].

Wang and Christopher noted that satellite imagery is a useful tool to monitor aerosols and their mode of transport due to the satellite's capability to collect repeated

measurements over large spatial areas when compared to ground measurements. In order to compare MODIS AOD to $PM_{2.5}$ they averaged the hourly $PM_{2.5}$ data centered on satellite overpass time and checked for possible cloud contamination based on the methodology outlined in *Chu et al.* [2002], showing that a good correlation existed between the $PM_{2.5}$ and AOD (linear correlation coefficient, $R = 0.7$) as derived from the MODIS satellite, suggesting that $PM_{2.5}$ is indicative of near surface values reflected in the MODIS AOD column. Large values of 0.35 from July-September and smaller values of 0.1 in winter trended well as the MODIS AOD monthly mean followed the $PM_{2.5}$

In 2007, Kumar *et al.* analyzed data from four different sources to examine the relationship between AOD to $PM_{2.5}$ at ground levels. The data used were: (1) air quality ($PM_{2.5}$) monitoring data collected from 113 ground sites in metropolitan New Delhi, (2) AOD data obtained from NASA's Goddard Space Flight Center Earth Sciences Distributed Active Archive Center (DAAC), (3) meteorological data from the Indian Meteorological Department and (4) data from the National Climatic Data Center. These data were used to examine the relationship between $PM_{2.5}$ and AOD by addressing the following two objectives: 1) establish an empirical relationship between $PM_{2.5}$ collected at the ground surface in New Delhi and satellite based AOD and 2) determine whether AOD can effectively predict $PM_{2.5}$ and $PM_{10}$ at high spatiotemporal resolutions. The data were filtered using the following three methods prior to analyzing the data: First, the study included only $PM_{2.5}$ samples collected ±150 minutes of satellite crossing time. Second, data were limited to the months of October and November to minimize weather

conditions. Lastly, relative humidity (RH) was limited to ≤50% as RH has been shown to increase particle size; referred to as hygroscopic growth.

The results of the 2007, Kumar *et al.* study showed a significant positive association between AOD and $PM_{2.5}$ with the best association occurring ±45 min of the Terra satellite. However, the study noted that real-time samplers were used as a field experiment to collect PM data, whereas existing monitoring stations use gravimetric methods that require sampling periods of at least eight hours. Sources of air pollution, proximity to bodies of water, vegetation, weather conditions and seasonality have also been identified as factors that could affect the PM and AOD relationship.

Kloog *et al.* noted that satellite remote sensing, with its ability to collect repeated measurements over large spatial areas (Engel-Cox et al., 2004; Gupta et al., 2006; Koelemeijer et al., 2006; Liu et al., 2004), provides an important tool where surface $PM_{2.5}$ monitors are not available. However, it should be mentioned that there are two important limitations of using AOD data. The first is that AOD cannot be collected when clouds or snow are present, resulting in missing values. The second limiting factor of AOD is that AOD data are not point specific, but an average of a large area.

Yang *et. al.*, assessed the benefits of combining satellite, meteorological, and land use data to predict the spatiotemporal variability in $PM_{2.5}$ concentrations daily on a regional scale by developing a two-stage generalized additive model (GAM) used to represent conditions when AOD retrieval was successful and for times when AOD

retrieval was not. The GAM was required because AOD data are often missing due to cloudy conditions, surface reflectance (i.e. snowy conditions), or retrieval errors.

In 2012, Kloog *et al.* expanded on their previous study and analyzed $PM_{2.5}$ concentrations obtained from the U.S. Environmental Protection Agency (EPA) Air Quality System (AQS) database and the Interagency Monitoring of Protected Visual Environments (IMPROVE) network for the years 2000-2008. Analysis was achieved using spatiotemporal predictors of $PM_{2.5}$ across the Mid-Atlantic region. Spatial predictors for this study included percent of open space, population density, elevation, traffic density, and both $PM_{2.5}$ point area-source emissions, whereas temporal predictors of $PM_{2.5}$ included meteorological variables (temperature, wind speed, visibility and relative humidity). Meteorological data were obtained from the national climatic data center (NCDC) and limited to 26 weather stations that provided continuous daily data from 2000 to 2008. Grid cells were then matched to the closest weather station for meteorological variables. The results demonstrated how AOD could be used to predict daily concentrations of $PM_{2.5}$ in the Mid-Atlantic region and used to assess short and long-term exposures.

## Research Purpose

Burn pit emissions were purported to cause negative health effects to personnel deployed in support of OEF and OIF campaigns where burn pits were used as the primary source to dispose of waste. Although a recent study [1] did not conclusively link PM to long-term health effects of personnel deployed to these regions, past studies have linked negative health effects to higher levels of PM [11] as well as specific elements.

The purpose of this study was to identify likely sources of $PM_{2.5}$ collected at Bagram Airfield (BAF), Afghanistan, determine how weather (wind-speed, wind-direction, temperature, and humidity) affects $PM_{2.5}$ measures, and if ground samples correlate to satellite Aerosol Optical Depth (AOD) data. The AOD data were used to determine if: 1) AOD values decreased as distance increased from the BAF burn pit, and 2) $PM_{2.5}$ and AOD are correlated.

**Hypotheses**

1: The source of airborne $PM_{2.5}$ can be determined using a combination of meteorological data, satellite Aerosol Optical Depth data and particulate matter sample data collected at ground level.

2: Aerosol Optical Depth data from satellites are correlated to particulate matter data obtained from ground-level sampling (as reported in DOEHRS).

**Objectives/Specific Aims**

Objective 1: Identify sources of $PM_{2.5}$

Specific Aim #1: Using ArcGIS, plot likely sources of $PM_{2.5}$ on a map

Specific Aim #2: Obtain rose diagrams of wind direction to show $PM_{2.5}$ movement and potential point of origin

Specific Aim #3: Use meteorological data to determine $PM_{2.5}$ dispersion (direction, speed, etc.) and plot using geographic information system (GIS) software

Objective 2: Establish relationship between $PM_{2.5}$ collected and AOD data

Specific Aim #1: Compare Satellite Aerosol Optical Depth (AOD) data at burn pits and surrounding areas to determine if AOD increased near burn pits

Specific Aim #2: Test whether AOD is correlated to ground measurements of $PM_{2.5}$

Objective 3: Identify meteorological conditions that may contribute to increased $PM_{2.5}$ levels

## Study Area

The study was centered on Bagram Airfield in Afghanistan. Geographically, Bagram Airfield (BAF) is located in northeast Afghanistan, approximately 200 kilometers from the Pakistan border (Figure 1). BAF lies in a relatively flat topographic basin surrounded by mountains. A heavily vegetated area, consisting of shrubs, crops, and grasslands [21] is located to the north and west of the airfield where whereas a dry desert landscape is present to the east and south (Figure 2).


Figure 1: Location of Bagram Airfield, Afghanistan in relation to surrounding countries and larger world view (inset).

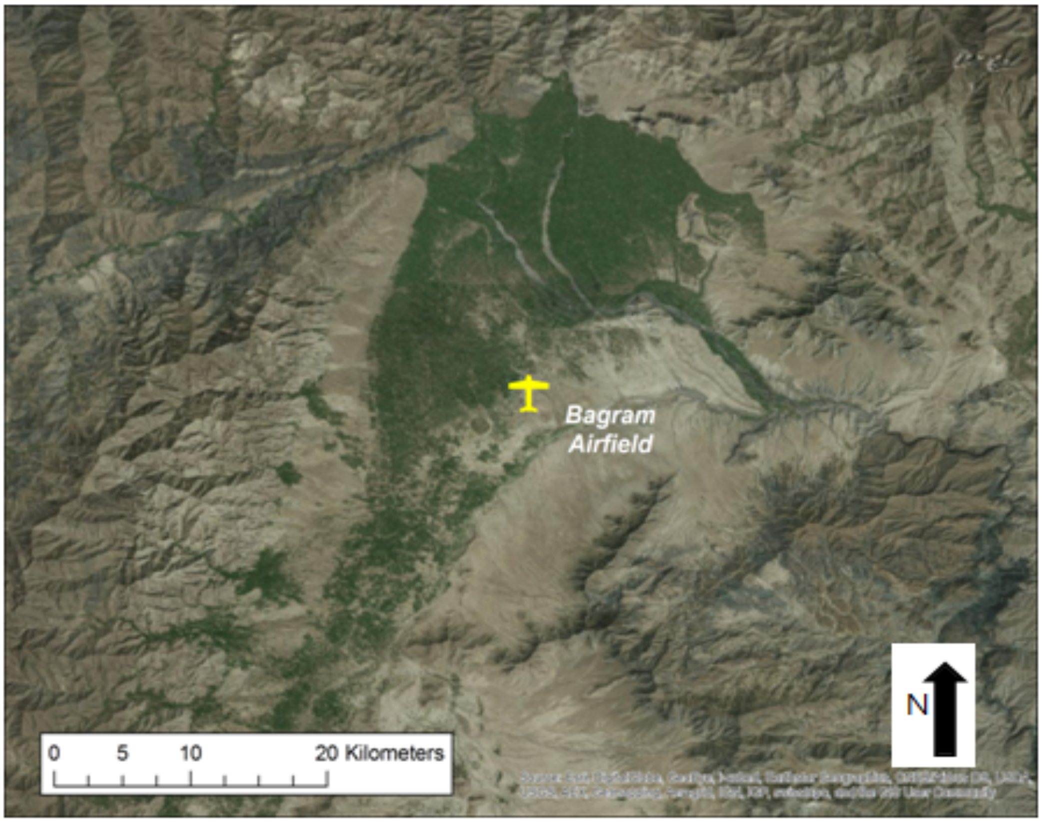


Figure 2: Satellite image of Bagram Airfield indicating that BAF sits in a basin surrounded by mountains, with a heavily vegetated area to the north and west and a dry sparsely vegetated area to the east and south of the airfield.

# CHAPTER 2: Methodology

## Data

Three databases were utilized to obtain the data used in this research project. The data include environmental sampling reports from the Defense Occupational and Environmental Health Readiness System (DOEHRS) obtained from the United States Army Public Health Command (USAPHC), meteorological data obtained from the United States Air Force 14th Weather Squadron, and Aerosol Optical Depth data obtained from the National Aeronautics and Space Administration (NASA). Data from the years 2006-2013 were used early in the study and narrowed based on data quality and consistency of data collection points.

Data obtained from the DOEHRS database, used in this project, include the following information collected at Bagram Airfield, Afghanistan:

- $PM_{2.5}$ sample site location (Name)
- Time sample was collected (24-hour period)
- Geographic grid coordinates (Latitude/longitude)
- Sample ID
- Concentrations of $PM_{2.5}$ collected over a 24-hour period

The DOEHRS data were entered into an Excel spreadsheet with the $PM_{2.5}$ data being converted to the logarithmic. The conversion to the logarithmic was necessary to normalize the data to follow a bell shaped curve and then averaged for further analysis.

The data obtained from the USAF 14th Weather Squadron contained the following information recorded daily from 1 January 2006 thru 31 December 2013:

- Date (Year/Month/Day)
- Hours of observation
- Average daily wind direction (i.e. N, NNE, ENE, NE, etc.)
- Mean wind speed (Knots)
- Maximum wind speed (Knots)
- Maximum daily temperature
- Minimum daily temperature
- Mean daily visibility (Meters)
- Minimum daily visibility (Meters)
- Hours daily precipitation
- Hours of smoke/haze
- Hours of dust
- Mean specific humidity (%)
- Mean relative humidity (%)

Aerosol Optical Depth (AOD) values were obtained from NASA Goddard Space Flight Center Level 1 and Atmosphere Archive and Distribution (LAADS) website: https://ladsweb.nascom.nasa.gov/. Upon request NASA reformatted and provided AOD values within the coordinates of 34.977 (N. Latitude), 34.913 (S. Latitude), 69.301 (E. Longitude) and 69.231 (W. Longitude) around BAF. This study used the Deep Blue/Dark Target combination data due to the mix of dense vegetation (dark targets) directly to the north and the desert, sandy region (bright targets) to the southeast of BAF. The following fields were used for this study:

- Date (Year/Month/Day)
- Time at start of collection
- AOD 550 Dark Target Deep Blue Combined
- Latitude
- Longitude

**DOEHRS Data Collection/Filtration**

The DOEHRS database was the initial source used in this study. The $PM_{2.5}$ data was the crux for this study and used to filter unneeded data from the two other databases. Additionally, the $PM_{2.5}$ concentration was used as the dependent variable throughout the analysis within this study.

Each record was opened individually to determine if the record contained usable data. Records were determined to be unusable if:

1. the record did not contain an entry for the amount of $PM_{2.5}$ collected

and/or

2. the record did not contain "Location (Name)" unless a valid grid coordinate identifying the sampling site was listed. Any record that the sampling point location could be identified, either by name or grid coordinate, was considered "usable" data and the record was retained as part of this study.

Using the grid coordinates obtained from DOEHRS, the locations of the $PM_{2.5}$ sampling points, burn pit, generator farm (Prime Power), weather station and zones were entered using GIS software and plotted on a map. BAF was divided into four equal sections to create zones. All $PM_{2.5}$ sampling sites were grouped by zone and PM concentrations were evaluated by zone as related to season and weather conditions. The zones were established by dividing BAF from north to south and east to west at the center of BAF (Figure 3).

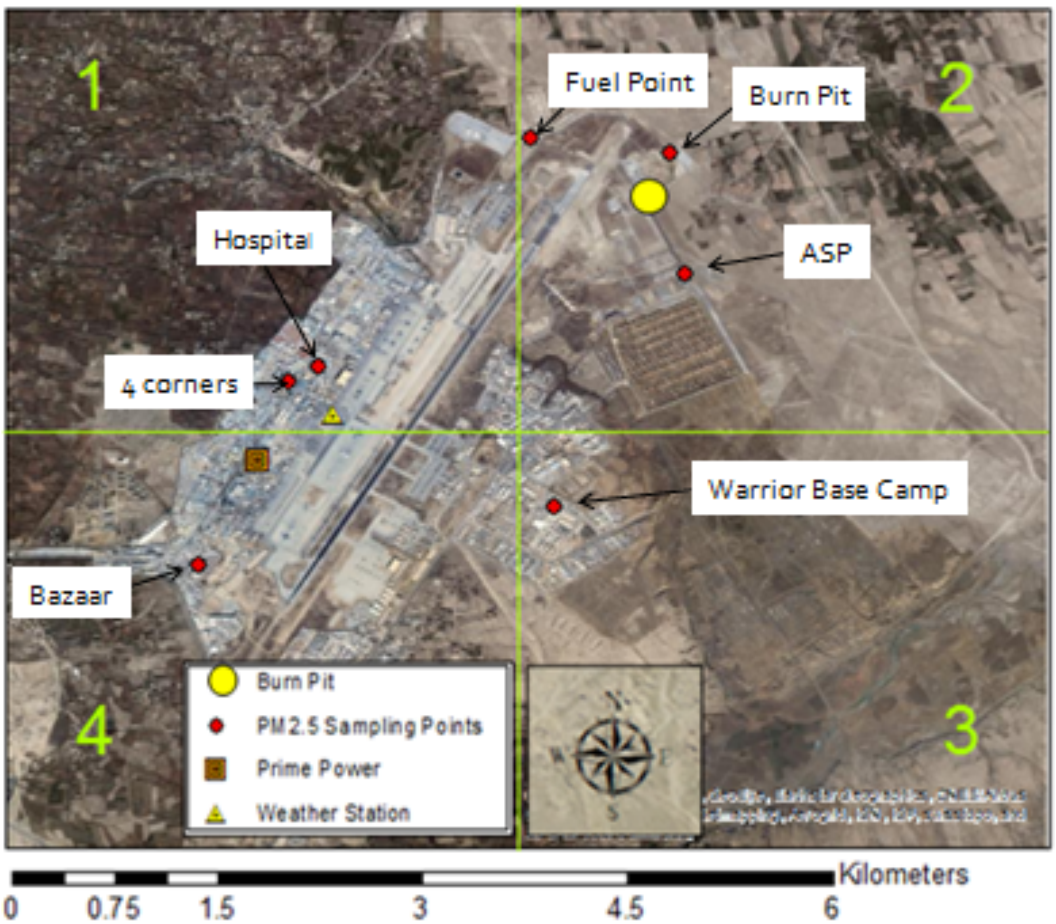


Figure 3: Satellite image of Bagram Airfield showing four zones, burn pit location, $PM_{2.5}$ sampling points, Prime Power, and weather station

**AOD Data Collection/Filtration**

A total of 6825 AOD values, for the years 2007-2010, were extracted for the study area and imported into ArcGIS and plotted on a map. Using the location of the burn pit as the center point, linear and radial distances were obtained using the GIS buffer tool. Multiple ring buffers were established using concentric circles around the burn pit at distances of 1, 3, 5, 10, 15, 20, and 25 kilometers to obtain radial distances. AOD data points that fell outside of the 25km radius of the burn pit were eliminated using the intersect tool. Of the initial 6825 AOD values only 4984 values were located within the 25km radius. A linear regression model was used to determine if AOD values decreased as distance from the burn pit increased.

The AOD data were later compared to ground $PM_{2.5}$ measurements by selecting only AOD data that were collected while $PM_{2.5}$ sampling was actively conducted. Any AOD collections that were not captured when active $PM_{2.5}$ sampling was in process were omitted from this study. After matching the AOD and DOEHRS $PM_{2.5}$ data by date, 1559 AOD entries remained and were plotted on a map using ARCMAP10.2.2 software.

Aerosol Optical Depth values, represented by the yellow points, were captured using satellites equipped with MODIS around Bagram Airfield (indicated by the central green point). Heavily vegetated areas can be seen to the north and west of BAF and a dry less vegetated area is observed to the south and east (Figure 4). Vegetation typically aids in reducing the amount of blowing dust whereas areas with less vegetation in arid environments may have higher levels of PM.

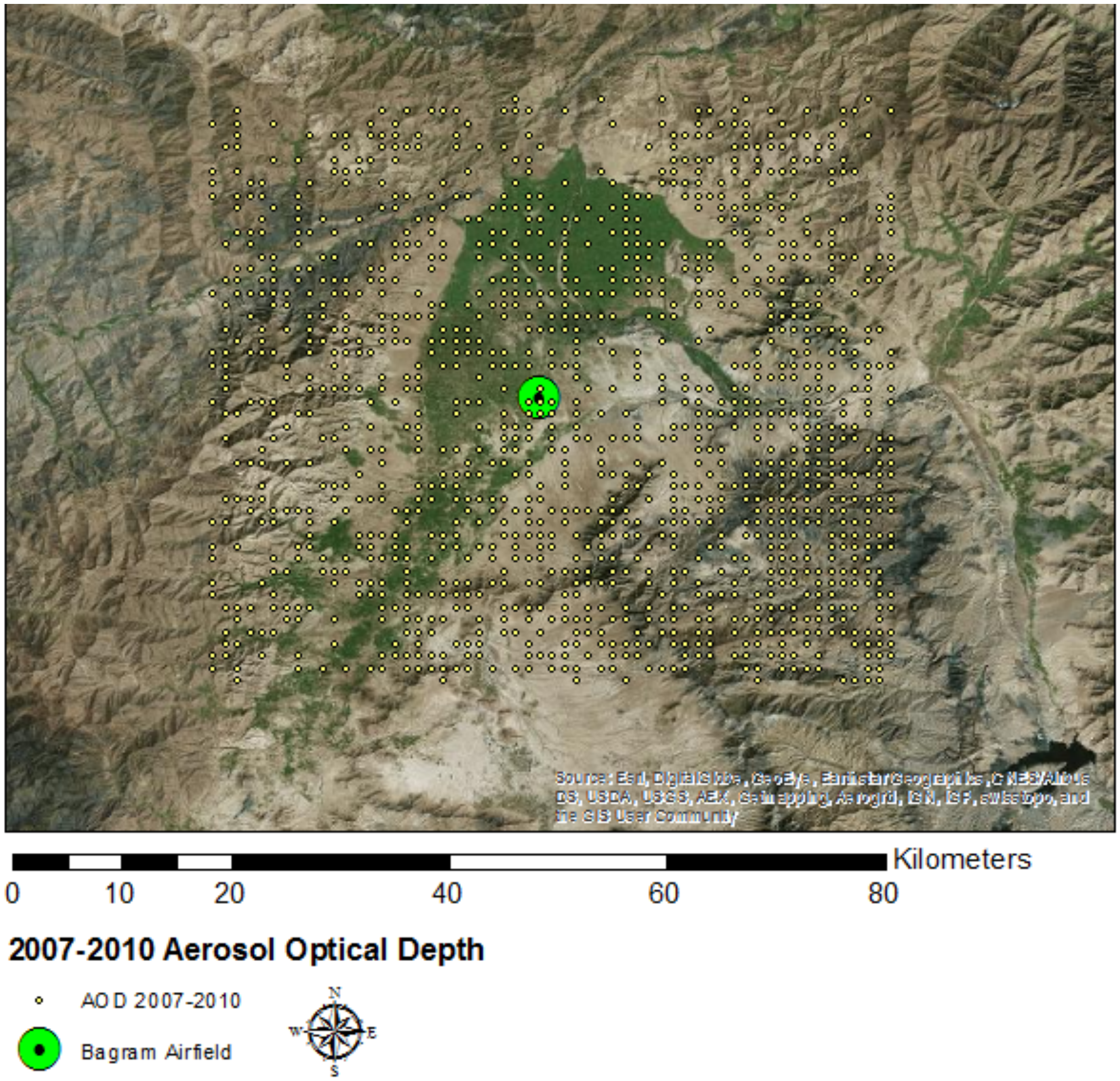


Figure 4: Satellite image of Bagram Airfield showing Aerosol Optical Depth collection sites from 2007 - 2010.

The data were further restricted using a 5km buffer or radius from the burn pit. Data were selected and compared using linear regression to determine if the $PM_{2.5}$ samples and AOD values collected on the same day were similar in magnitude. Of the

444 $PM_{2.5}$ collections, 34 data points (Appendix C) occurred when AOD data were captured within the 5km radius (Figure 5).

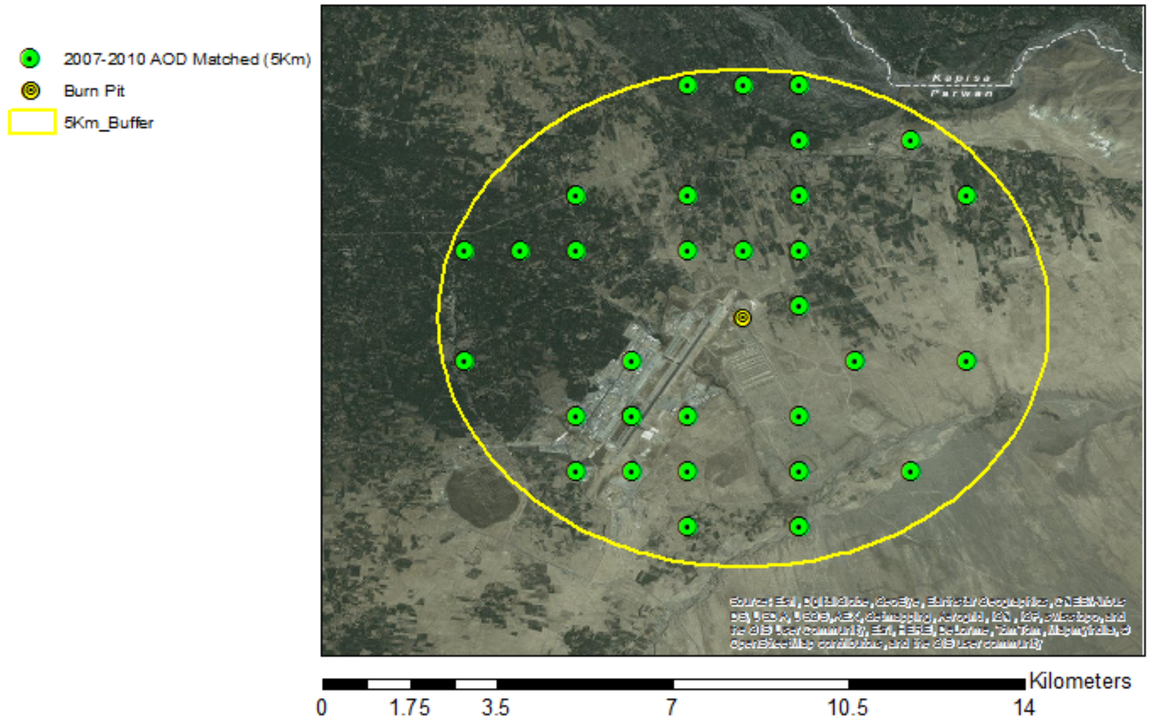


Figure 5: Satellite image of Bagram Airfield showing center points of Aerosol Optical Depth samples collected while $PM_{2.5}$ sampling was in progress from 2007 - 2010 within 5km of the burn pit.

# CHAPTER 3: Results and Discussion

The search of the DOEHRS database resulted in 1436 individual records, however many records failed to provide information for all fields. Two fields typically left blank were "Location (Name)" and "Grid Coordinate", however, the majority of the records usually contained either a valid "Location" or "Grid Coordinate" that allowed for positive identification of the sampling point. A total of 652 $PM_{2.5}$ records, were obtained from the DOEHRS database for the years 2006-2013. After further review, 82 of the 652 records failed to contain data required to make them "usable" (i.e. no $PM_{2.5}$ quantity, no valid location); reducing the total number of valid records to 570.

The $PM_{2.5}$ samples obtained in 2006 did not provide a valid grid coordinate or location name and were not used in this study. Additionally, the data for the years 2011, 2012, and 2013 were not used as the location of the burn pit and $PM_{2.5}$ sampling points changed, resulting in 444 remaining samples for the year 2007-2010 (Table 3).

Table 3: Total Number of DOEHRS $PM_{2.5}$ Records Retained for Study by Location, Zone and Year (2007-2010)

| Location | Zone | 2007 | 2008 | 2009 | 2010 | Total by Zone |
|---|---|---|---|---|---|---|
| 4 Corners | 1 | 12 | 42 | 46 | 37 | 147 |
| Hospital | 1 | 10 | - | - | - | |
| ASP | 2 | - | 5 | - | - | 228 |
| Burn Pit | 2 | - | 8 | 37 | 41 | |
| Fuel Point | 2 | 15 | 42 | 42 | 38 | |
| Warrior Base Camp | 3 | - | - | - | 4 | 4 |
| Bazaar | 4 | - | 5 | 37 | 23 | 65 |
| Total Samples | | 37 | 102 | 162 | 143 | 444 |

The $PM_{2.5}$ samples were grouped by zone and season to determine if $PM_{2.5}$ sampling was conducted consistently over space (zone) and time (season). Zone three was omitted due to the low number of $PM_{2.5}$ samples collected (N = 4) during the time of the study. The remaining 440 $PM_{2.5}$ samples collected in zones 1, 2, and 4 were distributed as follows zone 1 = 147, zone 2 = 228, zone 4 = 65. Seasonal $PM_{2.5}$ sampling was collected more consistently, with each season having at least 104 samples over the four year period (Table 4).

Table 4: Between-Subjects Factors matching $PM_{2.5}$ samples by zone and season (Zone 3 omitted due to low number of $PM_{2.5}$ samples)

| | | N |
|---|---|---|
| Zone | 1 | 147 |
| | 2 | 228 |
| | 4 | 65 |
| Season | Winter | 107 |
| | Spring | 115 |
| | Summer | 104 |
| | Fall | 114 |

Concentric rings were established at intervals of 1, 3, 5, 10, 15, 20, and 25 kilometers of the burn pit located at BAF (Figure 6). AOD values that fell outside of the 25 kilometer radius were omitted from this study. The remaining were placed in categories based on which concentric ring they fell inside. The concentric rings indicated the distance from the burn pit and were used to determine if AOD was reduced as distance increased from the burn pit.

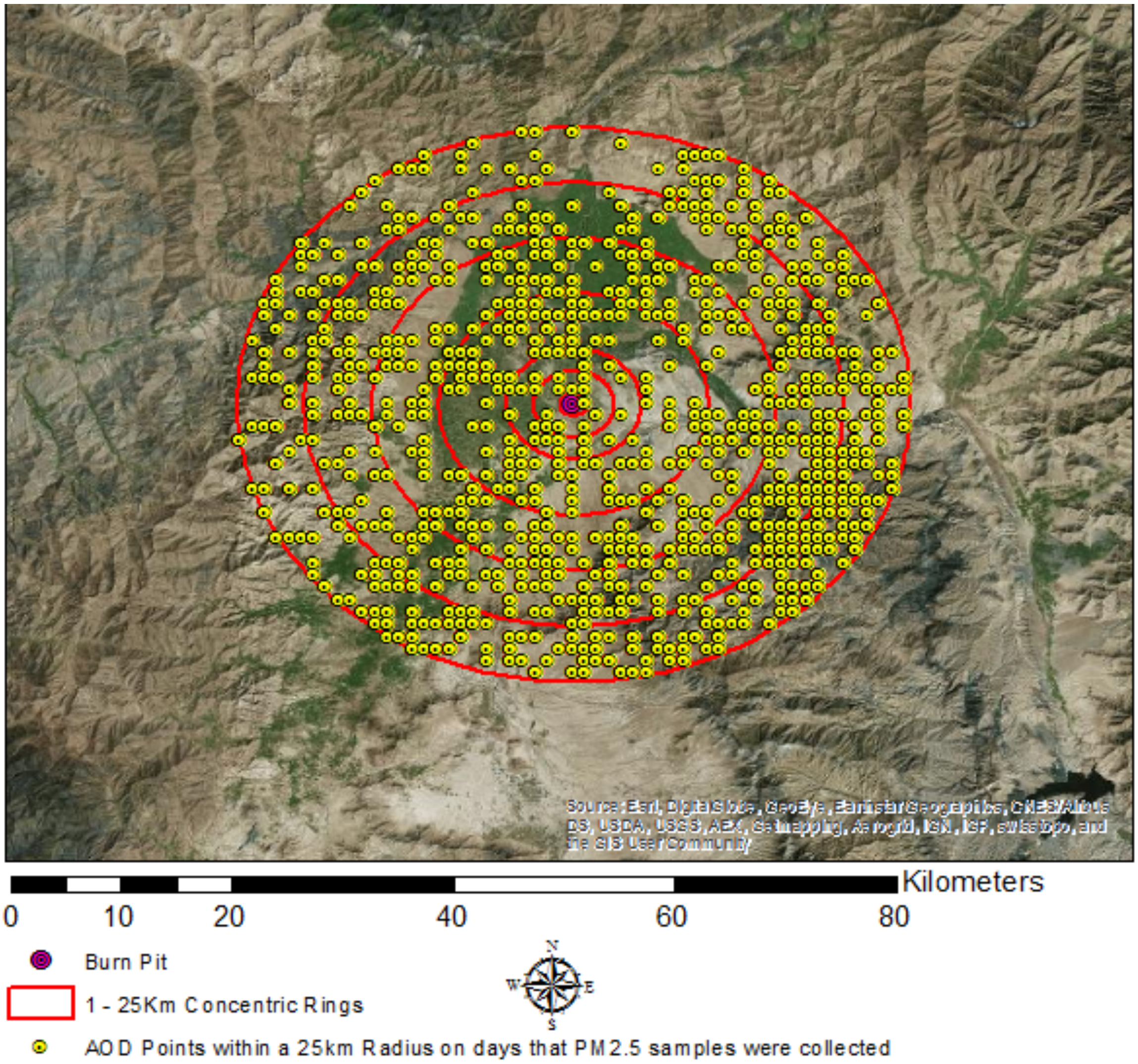


Figure 6: Satellite image of Bagram Airfield showing Aerosol Optical Depth collection center points from 2007 - 2010 within 25km of the burn pit. Concentric rings located at 1, 3, 5, 10, 15, 20, and 25 kilometer radius from burn pit.

The AOD values in Fig. 6 were exported from ArcGIS to an Excel spreadsheet to determine the effect of distance from the burn pit on the value of AOD. AOD values within 5 kilometers (Km) of the burn pit were selected and compared to the average $PM_{2.5}$ concentrations at BAF. The AOD values were matched by date with $PM_{2.5}$

samples, represented by green dots (Figures 7). Appendix C lists the AOD and $PM_{2.5}$ data compared in this section to determine if AOD and $PM_{2.5}$ obtained within a 5km area within a 24hour period were correlated.

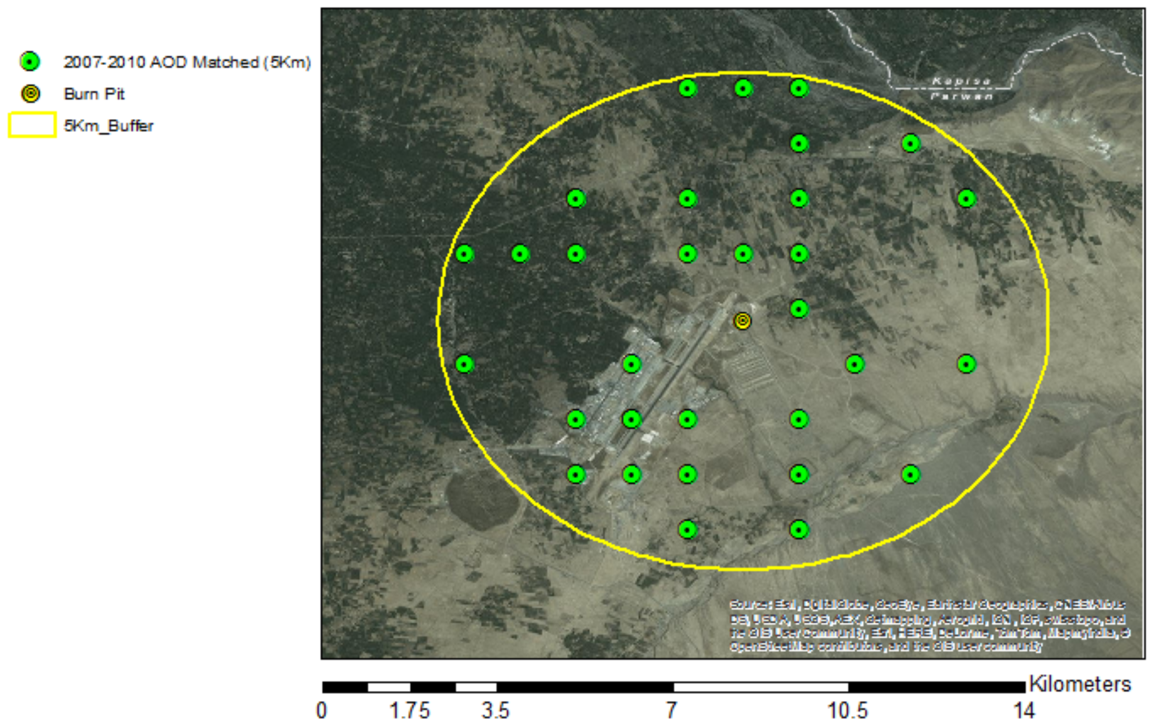


Figure 7: Satellite image of Bagram Airfield showing only Aerosol Optical Depth collected while $PM_{2.5}$ sampling was in progress from 2007 - 2010 within 5km of the burn pit.

An analysis of the AOD values falling within multi-ring buffer zones found that as distance increases AOD decreases by 3.6% (Table 5). Although AOD values decreased as distance increased from the burn pit, AOD collections within 5 km of the burn pit were limited, most likely a result of a smaller surface area compared to the area inside a 10 or 20 kilometer buffer zone. Additionally, no correlation was observed when

comparing AOD to $PM_{2.5}$ within a 5km radius of the burn pit, which may be attributed to the limited number of matched AOD and $PM_{2.5}$ samples collected within that area. Other factors that could contribute to the lack of significant correlation between AOD and $PM_{2.5}$ include: the difference in size between AOD pixels (10 km) versus the very localized ground $PM_{2.5}$ samples and the difference in the sampled time periods.

$PM_{2.5}$ collected at BAF was obtained over a 24-hour period and was not conducted in conjunction of satellite overpass. Therefore, this study, retrospectively looked at all $PM_{2.5}$ samples collected at BAF and used AOD data collected within a 24-hour period after $PM_{2.5}$ sampling began.

Table 5: Non-parametric correlation between AOD and Distance to burn pit in kilometers

| | | | AOD | Distance in km |
|---|---|---|---|---|
| Spearman's | AOD | Correlation Coefficient | 1.000 | -.361** |
| | | Sig. (2-tailed) | . | .000 |
| | | N | 4984 | 4984 |
| | Distance to burn pit in kilometers | Correlation Coefficient | -.361** | 1.000 |
| | | Sig. (2-tailed) | .000 | . |
| | | N | 4984 | 4984 |

**. Correlation is significant at the 0.01 level (2-tailed).

Figures 8-11 show seasonal wind rose diagrams created by the US Air Force 14th Weather Squadron. The diagrams were created using seasonal data obtain at BAF from 2007-2010. Each diagram was created using the seasonal data from four years (2007-2010). Wind rose diagrams show direction, speed, and duration in which wind moves over time. The direction, speed, and duration that wind moves is important when collecting air samples and can be used to help determine the source of airborne pollutants such as $PM_{2.5.}$

Wind rose diagrams show direction using "blades" that point to the direction that the wind is blowing. The rear of the "blade" starts at the perimeter of the rose diagram and points toward the center. For example, in Fig. 8 the "blade" indicates that the primary wind is out of the southwest (220 degrees) and points to the direction that the wind is blowing (northeast). The length of the "blade" shows how often the wind blows in that direction. The longer the "blade" the more often the wind blows in that direction. Whereas, the shorter the "blade" the less it blows from that direction. Additionally, the multicolored segments of the "blades" represent the speed at which the wind blows and can be determined using the key. Again, the length of the colored segments represent how often wind blows at that speed and direction. In other words, the larger the colored segment, the more often the wind blows at that speed and direction.

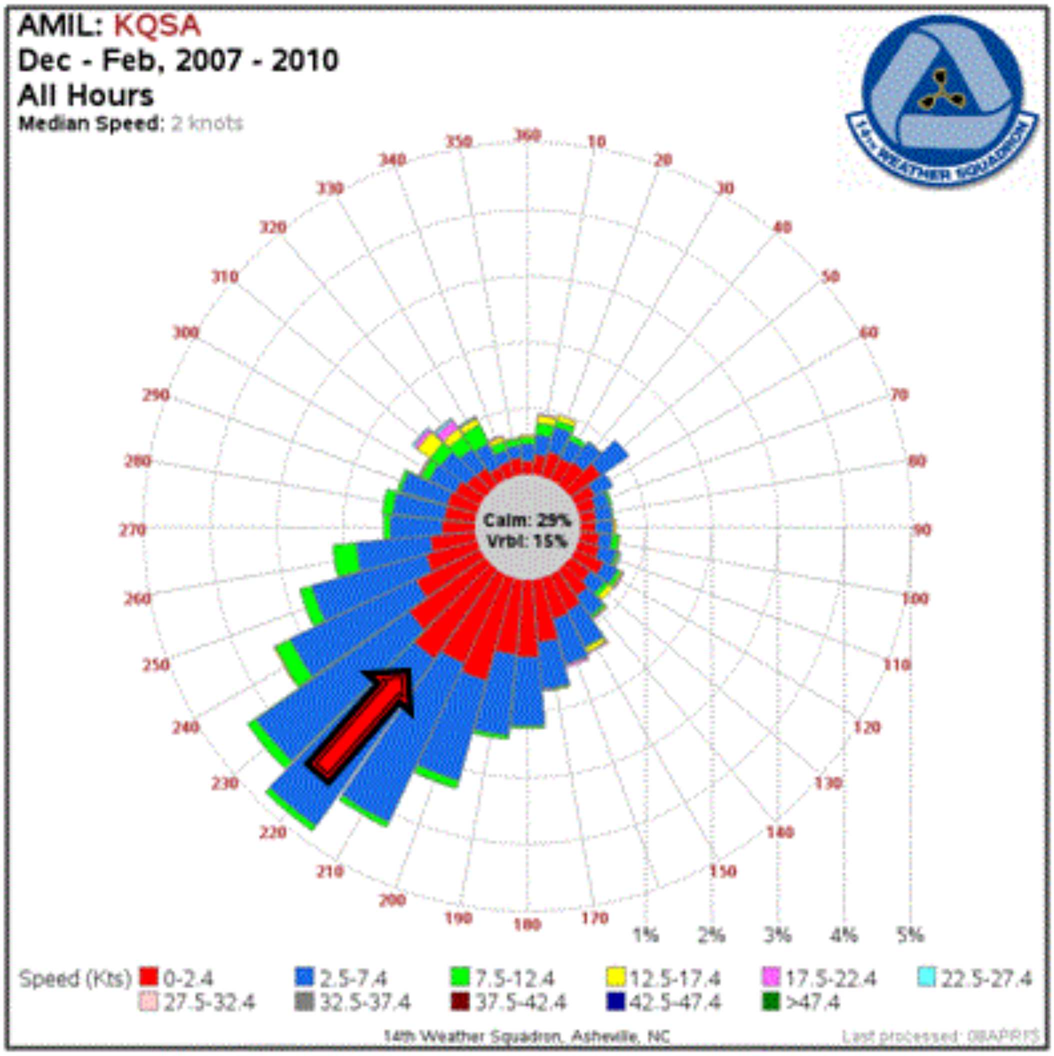


Figure 8: Seasonal wind rose diagram, provided by the USAF 14th Weather Squadron, depicting wind speed and direction for the winter months (December-February) 2007-2010 at Bagram Airfield (prevailing wind direction is indicated by the red arrow).

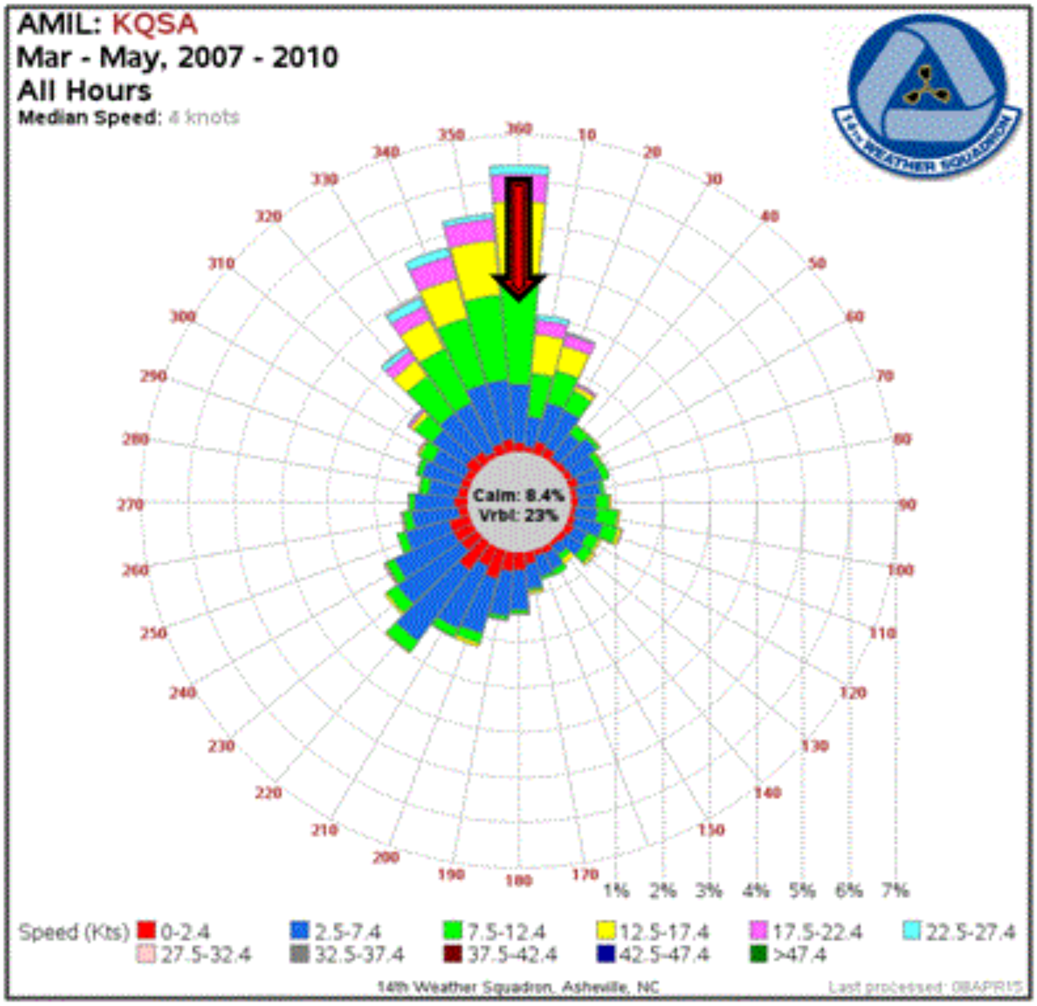


Figure 9: Seasonal wind rose diagram, provided by the USAF 14th Weather Squadron, depicting wind speed and direction for the spring months (March-May) 2007-2010 at Bagram Airfield (prevailing wind direction is indicated by the red arrow).

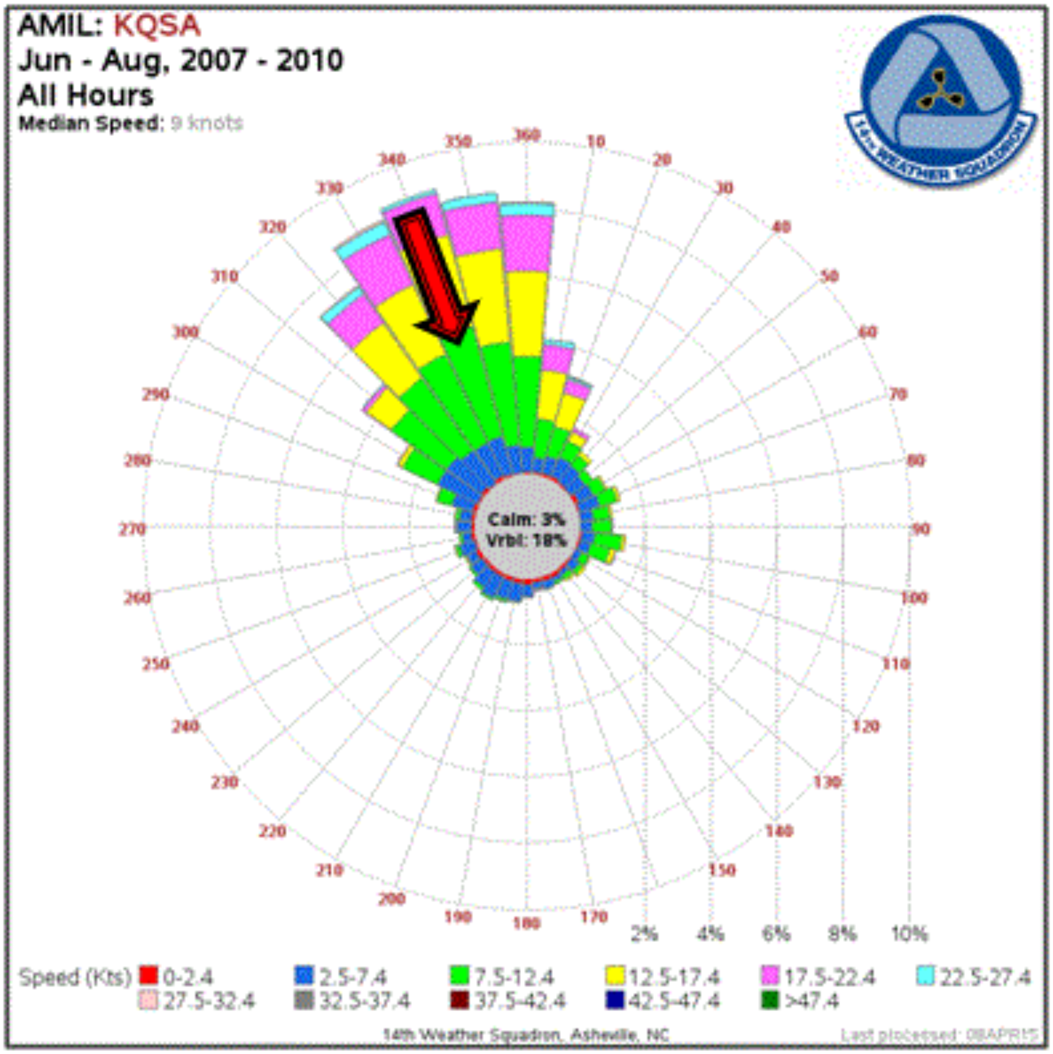


Figure 10: Seasonal wind rose diagram, provided by the USAF 14th Weather Squadron, depicting wind speed and direction for the summer months (June-August) 2007-2010 at Bagram Airfield (prevailing wind direction is indicated by the red arrow).

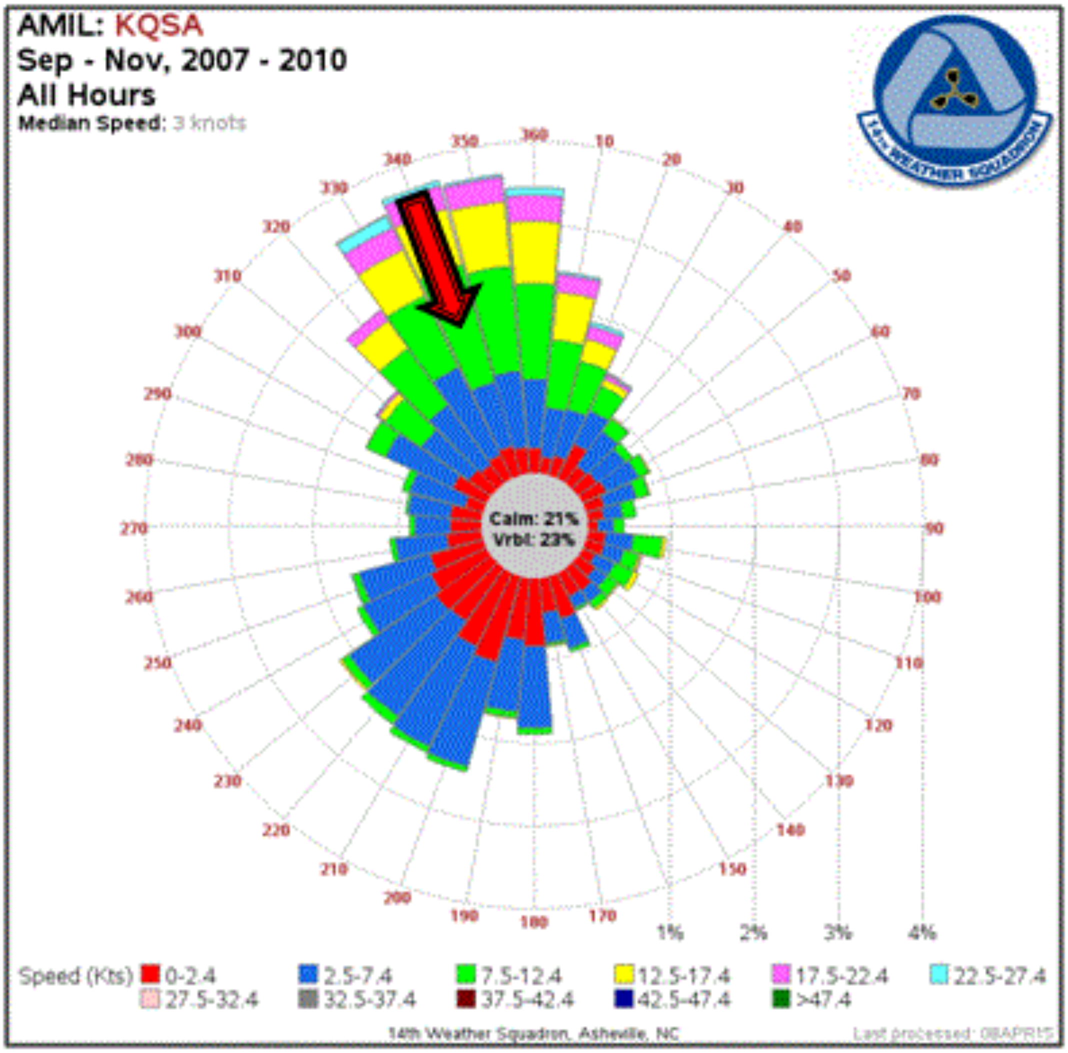


Figure 11: Seasonal wind rose diagram, provided by the USAF 14th Weather Squadron, depicting wind speed and direction for the Fall months (September-November) 2007-2010 at Bagram Airfield (prevailing wind direction is indicated by the red arrow).

As seen from the seasonal wind rose diagrams (Figures 8-11) the prevailing wind direction is from the north or northwest during the spring, summer, and fall (March-November). During the winter (December-February), the prevailing wind direction is from the southwest. Additionally, all wind exceeding 17 knots blow north to south.

A comparison of wind direction with a map of AOD values (Figure 12), shows that winds blow primarily from the north-northwest over a high AOD area. Thus, particulate matter may be moving from the northwest to BAF, indicating that the heavily vegetated area to the northwest may be a source of $PM_{2.5}$ at BAF (Figure 12). High particulate matter in the vegetated area may be due to transpiration from the vegetation, hygroscopic growth, fertilizers applied to the crops, or differences in the AOD measurement over vegetated versus non-vegetated areas.

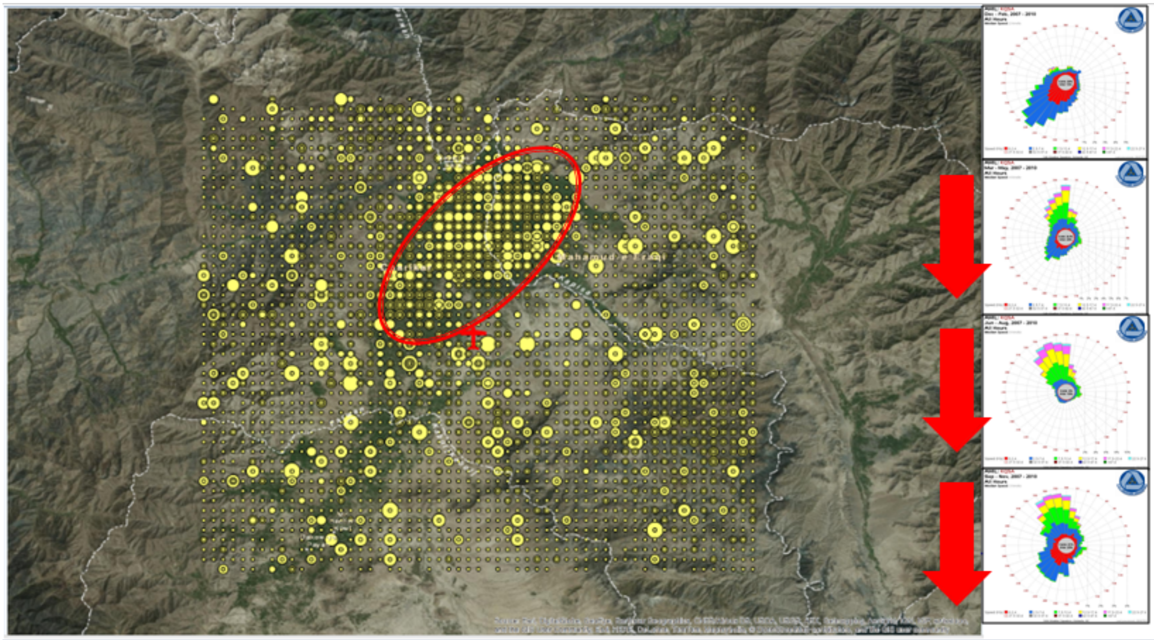

Figure 12: Cluster of AOD collections sites located to the north of BAF with wind rose diagrams indicating that the prevailing winds were blowing to the south, onto BAF, for nine months of the year.

This study used temperature, wind speed, and relative humidity as the three main meteorological predictor variables. Wind direction was also taken into consideration and used to determine likely sources of $PM_{2.5.}$ However, no speciation data were obtained or used in this study.

A test between subjects was run using wind speed, temperature, relative humidity, zone, and season to determine statistical significance when compared to $PM_{2.5.}$ Wind speed, relative humidity, and season were all statistically significant, whereas temperature and zone were not (Table 6). Statistical significance was observed in two of the three meteorological variables used in this study; Mean Speed ($p = 0.000$) and Mean

Relative Humidity (p = 0.000). Maximum temperature was also evaluated, however it was not statistically significant (p = 0.130) (Table 6). Although the three meteorological variables were not all statistically significant, each were observed to reduce $PM_{2.5}$ concentrations as they increased. $PM_{2.5}$ was reduced by 3%, 0.5%, and 0.6% as mean speed, max temp, and relative humidity increased, respectively, per unit of measure. Additionally, a post hoc (Tukey) test was run to check the results of the test between subjects, contradicting the previous results. The post hoc test showed that temperature was statistically significant (p = 0.006) whereas, relative humidity was not (p = 0.578).

The decrease in $PM_{2.5}$ may be inversely related to relative humidity due to hygroscopic growth which makes the particles larger and heavier (due to absorption of moisture) and/or stick together, thus increasing the overall size and weight of the particle. Since temperature was statistically significant in the first test and not in the second and the inverse is true for relative humidity; we may deduce that the two meteorological conditions may be related. Therefore, it makes sense that a decrease in $PM_{2.5}$ was also observed as temperature increased in the first test.

Table 6: Test of Between-Subjects using the Log of $PM_{2.5}$ as the dependent variable

Dependent Variable: Log $PM_{2.5}$

| Source | Type III Sum of Squares | Mean Square | F | Sig. |
|---|---|---|---|---|
| Mean Speed Knots | 3.487 | 3.487 | 45.685 | .000 |
| Max Temp C | .175 | .175 | 2.297 | .130 |
| Mean RH | 2.121 | 2.121 | 27.784 | .000 |
| Zone | .065 | .032 | .424 | .655 |
| Season | 1.575 | .525 | 6.880 | .000 |
| Zone * Season | .821 | .137 | 1.793 | .099 |

a. R Squared = .241 (Adjusted R Squared = .216)

Higher humidity and higher wind speed were both significant (Table 7) and could be used as independent predictors of $PM_{2.5}$. Although, temperature was not statistically significant in the test between subjects it was statistically significant when the post hoc was run. Therefore the decrease seen in $PM_{2.5}$ as temperature increased indicates that temperature may be associated with wind speed and RH and therefore, may be used as an independent predictor of $PM_{2.5}$ as well.

Table 7: Parameter estimates using the Log of $PM_{2.5}$ as the dependent variable showing p-values (sig.) and Beta indicating a decrease in $PM_{2.5}$ as Mean Speed, Max Temp, and Mean RH increase.

**Parameter Estimates**

Dependent Variable: Log $PM_{2.5}$

| Parameter | B | Std. Error | t | Sig. | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| | | | | | | |
| Mean Speed Knots | -.030 | .004 | -6.759 | .000 | -.039 | -.021 |
| Max Temp C | -.005 | .003 | -1.516 | .130 | -.012 | .002 |
| Mean RH | -.006 | .001 | -5.271 | .000 | -.008 | -.003 |

Table 8:The Mean and Standard Deviation (SD) of the Log of $PM_{2.5}$ and Mean Speed in Knots

| | Mean | Std. Deviation | N |
|---|---|---|---|
| Log $PM_{2.5}$ | 1.9571 | .31486 | 444 |
| Mean Speed (Knots) | 5.49 | 4.426 | 444 |

A scatter plot was created to display the relationship between wind speed and $PM_{2.5}$ concentrations (Figure 13). At first glance it appears that as wind speed increases, the concentration of $PM_{2.5}$ decreases. However, the number of $PM_{2.5}$ samples were not equally distributed amongst the different wind speeds.

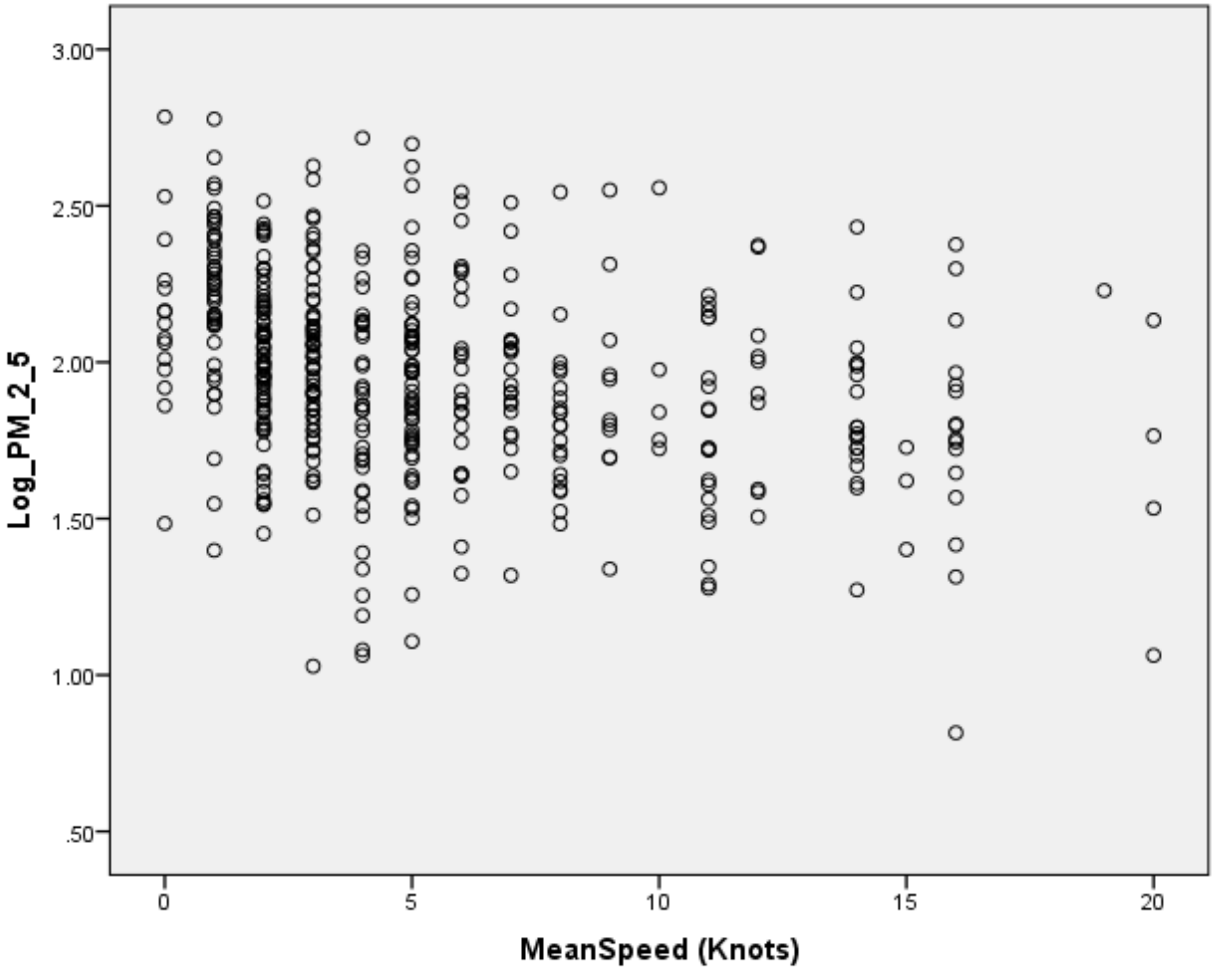


Figure 13: Scatter plot showing the Log of $PM_{2.5}$ and mean wind speed in knots indicating the higher the wind speed the lower the $PM_{2.5}$ concentration.

ANOVA was used to retest the relationship between zone and $PM_{2.5,}$ confirming that the location (zone) of $PM_{2.5}$ sampling sites was not statistically significant ( p, 0.231), therefore no location differed from another. If any zone was identified as statistically significant, ANOVA would show which location was different from the others. Therefore $PM_{2.5}$ concentrations were similar across BAF when compared to zone. Day to day variability is most likely a bigger factor than location in amount of $PM_{2.5}$ collected.

The $PM_{2.5}$ location (zone) was not statistically significant ($p = 0.231$), indicating that no location differed from another where significance is obtained at 0.05 (Table 9).

Table 9: ANOVA used to determine if location of $PM_{2.5}$ samples was statistically significant

Log $PM_{2.5}$

| | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Between Groups | .427 | 3 | .142 | 1.440 | .231 |
| Within Groups | 43.492 | 440 | .099 | | |
| Total | 43.919 | 443 | | | |

The location of the $PM_{2.5}$ sampling sites were not statistically significant (p, 0.231), meaning that no individual $PM_{2.5}$ sampling location observed a higher or lower amount of $PM_{2.5}$ consistently over time. Wind direction as related to the location of the burn pit was not statistically significant either. No trend was observed in $PM_{2.5}$ concentrations when season and location were compared to corresponding wind rose diagrams and the location of the burn pit. As a result, identifying the burn pit as the main source of $PM_{2.5}$ was not achieved in this study.

Table 10: Estimated Marginal Means comparing Zone and Season to the Log of $PM_{2.5}$ as the dependent variable.

Dependent Variable: Log $PM_{2.5}$

| Zone | Season | Mean | Std. Error | 95% Confidence Interval | |
|---|---|---|---|---|---|
| | | | | Lower Bound | Upper Bound |
| 1 | Winter | 1.974[a] | .060 | 1.857 | 2.092 |
| | Spring | 1.813[a] | .043 | 1.729 | 1.896 |
| | Summer | 2.010[a] | .060 | 1.892 | 2.128 |
| | Fall | 1.954[a] | .046 | 1.863 | 2.045 |
| 2 | Winter | 1.990[a] | .053 | 1.887 | 2.094 |
| | Spring | 1.891[a] | .037 | 1.818 | 1.965 |
| | Summer | 1.947[a] | .050 | 1.849 | 2.044 |
| | Fall | 2.027[a] | .036 | 1.956 | 2.098 |
| 4 | Winter | 2.127[a] | .072 | 1.985 | 2.269 |
| | Spring | 1.821[a] | .072 | 1.680 | 1.963 |
| | Summer | 2.026[a] | .075 | 1.878 | 2.174 |
| | Fall | 1.878[a] | .074 | 1.732 | 2.024 |

a. Covariates appearing in the model are evaluated at the following values: Mean Speed (Knots) = 5.532, Max Temp C = 22.273, Mean RH (%) = 43.118.

PM was not consistently high or low in any one zone over time, indicating there was no overall difference between the zones. The inconsistency of $PM_{2.5}$ was noted in table 6 indicating that it is not statistically significant given the p-value of 0.099 for the interaction between zone and season. However, Fig. 14 better illustrates the inconsistent trend using a line graph. $PM_{2.5}$ was highest in zone four during the winter and lowest during the fall when compared to zones 1 and 2. Levels of $PM_{2.5}$ were similar in zones

four and one during the spring and summer months, both were lower than zone two in the spring and higher than zone two in the summer. Zone two showed the least amount of fluctuation in terms of levels of $PM_{2.5}$ sampled. Zone two is also the zone where the burn pit is located which may indicate that the $PM_{2.5}$ concentrations in this zone are influenced more by the burn pit than the other zones reflecting the limited fluctuation.

The R-squared of 0.241, observed at the bottom of table 6, indicate that zone, season, wind speed, temperature and relative humidity together explain 24% of the variance in $PM_{2.5}$. $PM_{2.5}$ measured lowest during the spring season for all zones, whereas $PM_{2.5}$ measured higher in all three zones during the winter, summer, and fall seasons; however no one zone was consistently the highest or lowest.

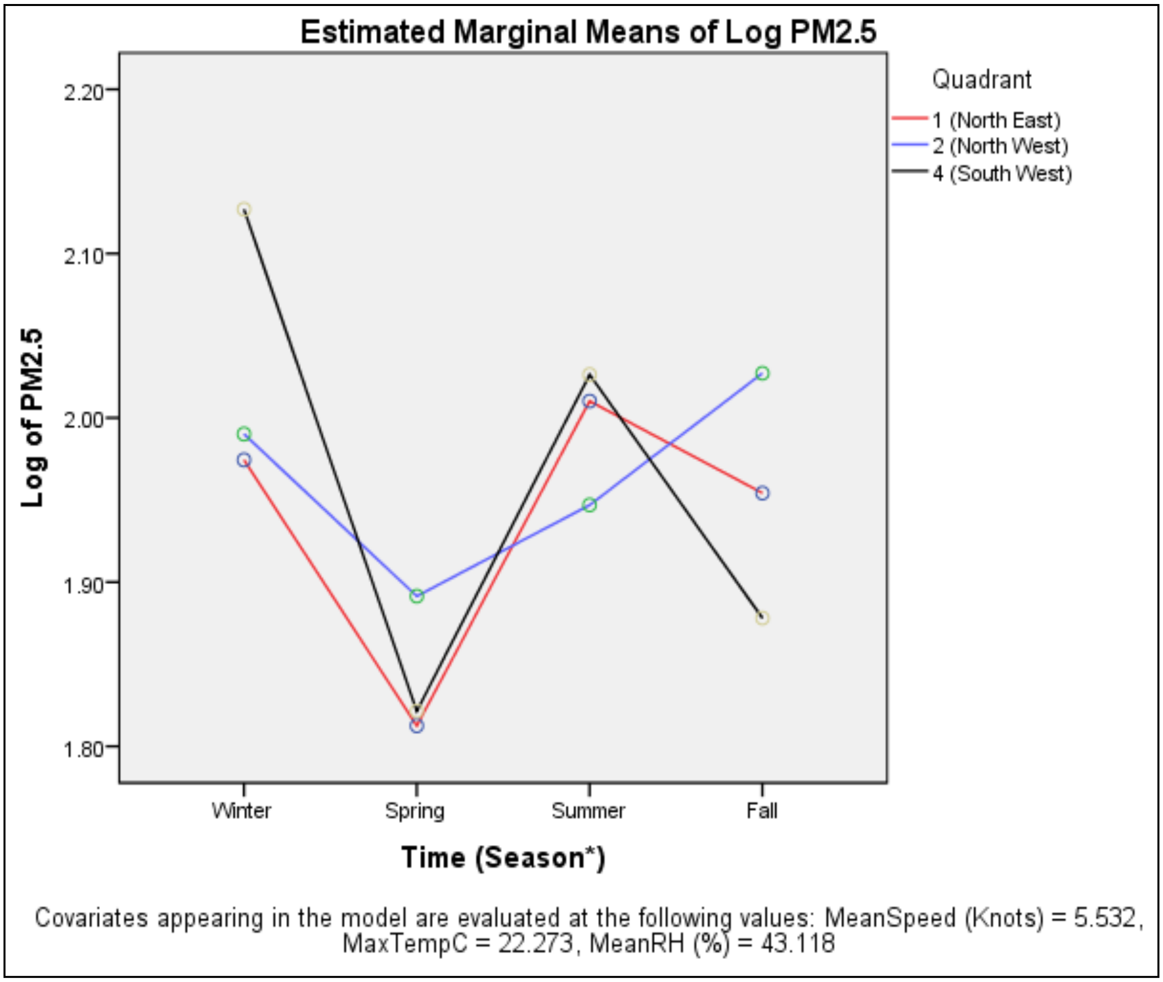


Figure 14: Line Graph comparing the Log of $PM_{2.5}$ and Season by Zone

$PM_{2.5}$ may be the lowest during the spring months as a result of the wet climate during this time of year, resulting in less airborne geological dust, limiting the amount of "smoke" emitted from the burn pit, and increased relative humidity. Whereas the winter, summer and fall seasons showed higher levels of $PM_{2.5}$ that may be attributed to temperature inversions, dryer climate, more windblown dust, and possibly the amount and type of waste burned in the burn pit.

# CHAPTER 4: Conclusions

This study focused on two hypotheses. The first was to determine the source of $PM_{2.5}$ at Bagram Airfield, Afghanistan, using a combination of meteorological data, satellite Aerosol Optical Depth data and particulate matter sample data collected at surface level. The second was to correlate the AOD from satellites to the $PM_{2.5}$ obtained from ground-level sampling as reported in DOEHRS to determine if available AOD data could be used to predict PM where sampling is not yet conducted by military personnel.

Although this study did not identify a specific source of $PM_{2.5}$ at BAF, the burn pit, prime power, and geological material (sand/dust) are likely sources and were plotted using GIS software (Figure 2). Additionally, a large cluster of AOD values were identified using GIS over the heavily vegetated area to the northwest of BAF (Figure 9). Wind rose diagrams indicate that prevailing winds blow north to south nine months out of the year, blowing the PM (as identified by the high AOD values) recorded over the heavily vegetated area toward BAF and possibly making a source not located on BAF the most likely source of $PM_{2.5}$ in this area.

Furthermore, wind direction, when associated to the burn pit location was determined not to influence the amount of $PM_{2.5}$ collected at sampling points. The wind rose diagrams show that the burn pit was placed in an optimal location based on prevailing winds to limit the amount of burn pit emissions at BAF. Additionally, zone 4 had the highest $PM_{2.5}$ concentration in winter when winds blew from southwest to

northeast restricting the burn pit emissions from entering the zone indicating that the burn pit was not the primary source of $PM_{2.5}$ in zone 4 during the winter seasons.

The use of concentric rings to calculate AOD distance from the burn pit and average the AOD values within the rings, resulting in AOD values decreasing by more than 3% as distance increased from the burn pit (Table 5) as speculated in objective 2. The least amount of AOD collections occurred within in 5 km of the burn pit, most likely a result of the smaller surface area when compared to outer rings. Variables confounding this outcome include variances in ground cover, point source emissions, elevation, and the mixing effect created by air movement around objects. Linear distance instead of concentric rings to determine distance may have resulted in a different, more accurate, outcome as the variables would be more easily identified and AOD values could be used at face value. Linear distance to determine point source and ground cover should be looked at in future work.

A positive correlation between AOD and $PM_{2.5}$ collected within a 5km radius of the burn pit at BAF was not identified in this study. The limited number of data points (34) obtained over the four year period may have resulted in the inability to positively correlate the two. Obtaining $PM_{2.5}$ data daily at a grid coordinate where AOD is captured may produce a better outcome and prove that AOD could be used when $PM_{2.5}$ sampling is not conducted. Additionally, selecting a month where cloud cover, snow and ice are minimized would be ideal to advance this study.

$PM_{2.5}$ concentrations decreased as meteorological data, specifically wind speed, temperature, and relative humidity increased individually per unit of measure. This could be advanced further using the AQI or MEG cut points for $PM_{2.5}$ and identifying trends by examining meteorological events individually to determine which events occur most often when PM is low or high. Additionally, point source emissions and sampling conducted for periods less than 24hrs may produce more accurate outcomes.

## LIMITATIONS

One limitation of this study was that there were inconsistent $PM_{2.5}$ and AOD collections over space and time. The search of the DOEHRS database resulted in many incomplete records that could not be used in this study. Additionally, $PM_{2.5}$ samples were not collected on a consistent basis limiting the number of valid samples obtained from one or more locations.

Matching dates that AOD and $PM_{2.5}$ were collected were limited primarily due to a couple of factors. AOD is not captured when clouds are present in the atmosphere or when snow or ice is present on the surface of the earth. As mentioned previously, inconsistent $PM_{2.5}$ collections or incomplete data limited the matching possibilities with the AOD. Meteorological data were recorded daily over the duration of this study, however, the limited $PM_{2.5}$ data reduced the number of possible matched $PM_{2.5}$ samples and meteorological data from a possible 5840 samples (365/year/zone or 1460/year over four years) to 444 samples over the four year period.

## FUTURE RESEARCH

Determining the composition or speciation of the $PM_{2.5}$ collected on the sampling filters may help to better identify the source. Identifying whether the samples contain VOCs from the burn pit, black carbon from the generators, sand or dust, or a chemical/fertilizer from the agricultural area to the north may help to mitigate the risk by addressing the source and preventing or reducing the airborne PM. Additionally, identifying the composition of the $PM_{2.5}$ could prove useful to determine possible health effects that may be attributed to the inhalation of specific chemicals/substances. AOD could also be used to identify areas of low/high concentrations when ground sampling is not available to determine possible areas of operation if mission allows.

USAPHC-Main has already addressed many of these points. As recently as 2013 they conducted multiple sampling methods at Bagram. The multiple sampling methods included high volume, passive canister, battery powered sampling, and real time data logging for PM in addition to the typical sampling normally used by PM detachments. The multiple sampling methods may be of use to when looking at future $PM_{2.5}$ projects as a way to compare methods and identify sources.

This study used AOD data obtained from a 10km area, resulting in no correlation when compared to the available $PM_{2.5}$ data. A correlation between AOD and $PM_{2.5}$ may be observed using AOD data collected from a smaller area, such as 3km or a1km area, if available. Using the AOD values collected from a smaller area may be used to more accurately predict $PM_{2.5}$ for a specific location.

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# Appendix A: National Ambient Air Quality Standards (NAAQS)

The Clean Air Act, which was last amended in 1990, requires EPA to set National Ambient Air Quality Standards (40 CFR part 50) for pollutants considered harmful to public health and the environment. The Clean Air Act identifies two types of national ambient air quality standards. ***Primary standards*** provide public health protection, including protecting the health of "sensitive" populations such as asthmatics, children, and the elderly. ***Secondary standards*** provide public welfare protection, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings.

EPA has set National Ambient Air Quality Standards for six principal pollutants, which are called "criteria" pollutants. They are listed below. Units of measure for the standards are parts per million (ppm) by volume, parts per billion (ppb) by volume, and micrograms per cubic meter of air ($\mu g/m^3$).

| Pollutant [final rule cite] | Primary/ Secondary | Averaging Time | Level | Form |
|---|---|---|---|---|
| Carbon Monoxide [76 FR 54294, Aug 31, 2011] | primary | 8-hour | 9 ppm | Not to be exceeded more than once per year |
| | | 1-hour | 35 ppm | |
| Lead [73 FR 66964, Nov 12, 2008] | primary and secondary | Rolling 3 month average | 0.15 $\mu g/m^3$ (1) | Not to be exceeded |

| | | | | | |
|---|---|---|---|---|---|
| Nitrogen Dioxide [75 FR 6474, Feb 9, 2010] [61 FR 52852, Oct 8, 1996] | | primary | 1-hour | 100 ppb | 98th percentile of 1-hour daily maximum concentrations, averaged over 3 years |
| | | primary and secondary | Annual | 53 ppb [2] | Annual Mean |
| Ozone [73 FR 16436, Mar 27, 2008] | | primary and secondary | 8-hour | 0.075 ppm [3] | Annual fourth-highest daily maximum 8-hr concentration, averaged over 3 years |
| Particle Pollution Dec 14, 2012 | $PM_{2.5}$ | primary | Annual | 12 $\mu g/m^3$ | annual mean, averaged over 3 years |
| | | secondary | Annual | 15 $\mu g/m^3$ | annual mean, averaged over 3 years |
| | | primary and secondary | 24-hour | 35 $\mu g/m^3$ | 98th percentile, averaged over 3 years |
| | $PM_{10}$ | primary and secondary | 24-hour | 150 $\mu g/m^3$ | Not to be exceeded more than once per year on average over 3 years |
| Sulfur Dioxide [75 FR 35520, Jun 22, 2010] [38 FR 25678, Sept 14, 1973] | | primary | 1-hour | 75 ppb [4] | 99th percentile of 1-hour daily maximum concentrations, averaged over 3 years |
| | | secondary | 3-hour | 0.5 ppm | Not to be exceeded more than once per year |

(1) Final rule signed October 15, 2008. The 1978 lead standard (1.5 µg/m3 as a quarterly average) remains in effect until one year after an area is designated for the 2008 standard,

except that in areas designated nonattainment for the 1978, the 1978 standard remains in effect until implementation plans to attain or maintain the 2008 standard are approved.

(2) The official level of the annual NO2 standard is 0.053 ppm, equal to 53 ppb, which is shown here for the purpose of clearer comparison to the 1-hour standard.

(3) Final rule signed March 12, 2008. The 1997 ozone standard (0.08 ppm, annual fourth-highest daily maximum 8-hour concentration, averaged over 3 years) and related implementation rules remain in place. In 1997, EPA revoked the 1-hour ozone standard (0.12 ppm, not to be exceeded more than once per year) in all areas, although some areas have continued obligations under that standard ("anti-backsliding"). The 1-hour ozone standard is attained when the expected number of days per calendar year with maximum hourly average concentrations above 0.12 ppm is less than or equal to 1.

(4) Final rule signed June 2, 2010. The 1971 annual and 24-hour SO2 standards were revoked in that same rulemaking. However, these standards remain in effect until one year after an area is designated for the 2010 standard, except in areas designated nonattainment for the 1971 standards, where the 1971 standards remain in effect until implementation plans to attain or maintain the 2010 standard are approved.

## Appendix B: Revised air quality standards for particle pollution and updates to the Air Quality Index (AQI)

| AQI Category | Index Values | Previous Breakpoints (1999 AQI) (µg/m$^3$, 24-hour average) | Revised Breakpoints (µg/m$^3$, 24-hour average) |
|---|---|---|---|
| **Good** | 0 - 50 | 0.0 - 15.0 | 0.0 – 12.0 |
| **Moderate** | 51 - 100 | >15.0 - 40 | 12.1 – 35.4 |
| **Unhealthy for Sensitive Groups** | 101 – 150 | >40 – 65 | 35.5 – 55.4 |
| **Unhealthy** | 151 – 200 | > 65 – 150 | 55.5 – 150.4 |
| **Very Unhealthy** | 201 – 300 | > 150 – 250 | 150.5 – 250.4 |
| **Hazardous** | 301 – 400 | > 250 – 350 | 250.5 – 350.4 |
| | 401 – 500 | > 350 – 500 | 350.5 – 500 |

# Appendix C: AOD and $PM_{2.5}$ data extracted from Figure 7 using ARCGIS

| Km | Year | Month | Day | Time | $PM_{2.5}$ AVE | Log $PM_{2.5}$ | DB/DT AOD 550 | DB/DT AOD QA | Lat | Long |
|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 2007 | 10 | 18 | 810 | 182.51 | 2.26 | 0.091 | 3 | 34.94 | 69.26 |
| 5 | 2007 | 11 | 12 | 805 | 141.6 | 2.15 | 0.289 | 3 | 34.98 | 69.25 |
| 5 | 2007 | 11 | 24 | 830 | 184.77 | 2.26 | 0.14 | 3 | 34.99 | 69.29 |
| 5 | 2007 | 12 | 24 | 840 | 75.12 | 1.87 | 0.062 | 3 | 34.96 | 69.29 |
| 5 | 2007 | 12 | 29 | 900 | 60.2 | 1.77 | 0.079 | 3 | 34.98 | 69.32 |
| 5 | 2008 | 3 | 11 | 855 | 156.28 | 2.19 | 0.181 | 2 | 34.93 | 69.26 |
| 5 | 2008 | 4 | 16 | 830 | 54.12 | 1.73 | 0.12 | 2 | 34.97 | 69.27 |
| 5 | 2008 | 4 | 29 | 800 | 144.02 | 2.15 | 0.132 | 2 | 34.97 | 69.24 |
| 5 | 2008 | 6 | 17 | 840 | 99.23 | 1.99 | 0.503 | 3 | 34.97 | 69.23 |
| 5 | 2008 | 11 | 29 | 905 | 272.32 | 2.43 | 0.086 | 3 | 34.95 | 69.26 |
| 5 | 2008 | 12 | 21 | 825 | 179.94 | 2.25 | 0.057 | 3 | 34.95 | 69.32 |
| 5 | 2008 | 12 | 30 | 820 | 158.83 | 2.20 | 0.106 | 3 | 34.93 | 69.25 |
| 5 | 2009 | 3 | 30 | 900 | 89.35 | 1.95 | 0.129 | 2 | 34.97 | 69.28 |
| 5 | 2009 | 7 | 21 | 805 | 55.06 | 1.74 | 0.179 | 3 | 34.95 | 69.3 |
| 5 | 2009 | 7 | 28 | 810 | 49.9 | 1.69 | 0.228 | 2 | 34.98 | 69.27 |
| 5 | 2009 | 8 | 25 | 835 | 93.45 | 1.97 | 0.132 | 2 | 34.93 | 69.31 |
| 5 | 2009 | 9 | 8 | 845 | 169.09 | 2.22 | 0.143 | 2 | 34.94 | 69.29 |
| 5 | 2009 | 10 | 7 | 815 | 107.27 | 2.03 | 0.071 | 2 | 34.94 | 69.26 |
| 5 | 2009 | 10 | 14 | 820 | 105.14 | 2.02 | 0.196 | 2 | 34.99 | 69.31 |
| 5 | 2009 | 10 | 28 | 830 | 106.29 | 2.02 | 0.126 | 2 | 34.94 | 69.27 |
| 5 | 2009 | 11 | 11 | 845 | 193.01 | 2.28 | 0.127 | 3 | 35 | 69.29 |
| 5 | 2009 | 11 | 17 | 805 | 98.56 | 1.99 | 0.099 | 3 | 34.93 | 69.27 |
| 5 | 2009 | 12 | 24 | 825 | 93.98 | 1.97 | 0.051 | 3 | 34.94 | 69.25 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 2009 | 12 | 31 | 830 | 146.04 | 2.16 | 0.05 | 3 | 34.95 | 69.23 |
| 5 | 2010 | 1 | 21 | 850 | 158.09 | 2.19 | 0.094 | 3 | 34.97 | 69.25 |
| 5 | 2010 | 3 | 1 | 855 | 50.52 | 1.70 | 0.056 | 3 | 34.93 | 69.29 |
| 5 | 2010 | 4 | 12 | 755 | 75.18 | 1.87 | 0.071 | 2 | 34.94 | 69.26 |
| 5 | 2010 | 5 | 3 | 815 | 62.48 | 1.79 | 0.062 | 2 | 34.93 | 69.29 |
| 5 | 2010 | 6 | 28 | 900 | 96.2 | 1.98 | 0.21 | 2 | 34.98 | 69.29 |
| 5 | 2010 | 7 | 6 | 810 | 145.22 | 2.16 | 0.152 | 2 | 34.97 | 69.29 |
| 5 | 2010 | 9 | 22 | 825 | 134.7 | 2.12 | 0.192 | 2 | 35 | 69.29 |
| 5 | 2010 | 10 | 12 | 800 | 96.77 | 1.98 | 0.092 | 2 | 34.92 | 69.27 |
| 5 | 2010 | 10 | 26 | 810 | 48.39 | 1.68 | 0.095 | 2 | 34.98 | 69.25 |
| 5 | 2010 | 12 | 14 | 855 | 239.09 | 2.37 | 0.101 | 3 | 35 | 69.27 |